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The Optical Counterpart of the Supersoft Small Magellanic Cloud Transient Pulsar RX J0059.2-7138

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ABSTRACT

We identify the probable optical counterpart of the SMC supersoft source, RX J0059.2-7138, with a $\sim$ 14th magnitude star lying within the X-ray error circle. We present high resolution optical spectroscopy, which reveals strong HI emission and HeI absorption, indicative of a Be star. This classification is consistent with the colours we derive from optical photometry. We thus find evidence to support the existing tentative identification of this object as a Be/X-ray binary, the first of its kind to exhibit luminous supersoft X-ray emission.

Key words: stars: emission line, Be – pulsars: individual: RX J0059.2-71 – accretion, accretion discs – binaries: spectroscopic – X-rays: stars.

1 INTRODUCTION

The supersoft X-ray sources (SSSs) have been established by *ROSAT* observations as a new class of objects, characterised by their luminous ($L_{\rm bol} \sim 10^{37} - 10^{38}\,{\rm erg\,s^{-1}}$) emission at very soft X-ray energies ($T_{\rm bb} \sim 30 - 50$ eV) - see reviews by e.g. Kahabka & Trümper (1996); Cowley et al. (1996). The group as a whole is not strictly homogeneous; the archetypal sources, CAL 83 and CAL 87, originally discovered by the *Einstein* X-ray Observatory (Long, Helfand & Grabelsky, 1981) have the highest luminosities, and are popularly thought to be white dwarf binaries accreting at exceptionally high rates, due to thermally unstable mass transfer from a more massive donor star (van den Heuvel et al. 1992). However, luminous supersoft emission has also been observed from symbiotic systems (e.g. Hasinger 1994) and a planetary nebula nucleus (Wang 1991), although their bolometric luminosities are typically an order of magnitude lower.

The supersoft source RX J0059.2-7138 (hereafter RX J0059-71) was detected serendipitously with the *ROSAT* PSPC in 1993 May, at a count rate of $\sim 8\,{\rm s^{-1}}$, and was seen almost simultaneously by *ASCA* (Hughes 1994; Kylafis 1996). Previously, it had failed to be detected by either the *Einstein* Observatory or *EXOSAT* in the early 1980s, or in recent pointed *ROSAT* observations of 1991 November (see Hughes 1994). The transient nature of this source is thus clearly established.

The best fit to the X-ray spectrum consists of three components (Kylafis 1996): two power laws with indices of 0.7 and 2.0 fit the spectrum in the $>$ 3 keV and $0.5-3.0$ keV bands respectively. Furthermore, the emission is pulsed at a level of $\sim$ 35% and $\sim$ 20% in these respective bands, with a period of $\sim$ 2.7 s (Hughes 1994), firmly establishing the presence of a neutron star. *However, the lower energy band ($<$ 0.5 keV) requires the third spectral fit component, which accounts for $\sim$ 90% of the bolometric luminosity, and is a black body with a temperature $kT_{\rm bb} \sim 35$ eV.* Such luminous supersoft emission is clearly unexpected in this object, given the van den Heuvel et al. (1992) accreting white dwarf binary model for the SSSs.

On the basis of its X-ray properties, Hughes (1994) tentatively identified RX J0059-71 as a high mass X-ray binary, possibly a Be/X-ray binary system (see e.g. Parmar 1994 for a review of these objects). We have therefore undertaken optical spectroscopy and photometry of the proposed counterpart, to investigate the nature of this potentially unusual member of the SSSs.

2 OPTICAL SPECTROSCOPY AND PHOTOMETRY

2.1 Observations and Reduction

Spectroscopy of the proposed counterpart was obtained in Nov/Dec 1994 using the 3.9 m Anglo-Australian Telescope at Siding Spring. The detector was a 1024×1024 TEK CCD attached to the RGO spectrograph. The 1200V grating on the 25 cm camera gave a resolution of $\sim$ 1.3 Å. In addition, a single spectrum was obtained using an identical set-up in Jan 1996. Tab. 1 lists the journal of spectroscopic observations. Cu-Ar arc spectra were taken before or after each object exposure, and a series of tungsten lamp flat fields and bias frames were also obtained. Owing to poor observing

conditions (variable cloud) during both runs, no flux standards were observed, and hence the data were not corrected for instrumental response. Reduction of the data frames followed standard procedures. We subtracted the bias signal, and removed small scale pixel-to-pixel sensitivity variations by multiplying by a balance frame prepared from the tungsten lamp flat fields. One dimensional spectra were extracted using the optimal algorithm of Horne (1986), and conversion of the pixel scale to wavelength units was achieved using the arc calibration spectra.

CCD photometry of the target field was obtained in 1996 Jan, using the UCT CCD on the 1.9m telescope at the South African Astronomical Observatory, Sutherland. We used standard 'BV (Johnson) and R (Cousins) filters. Flat fields of the twilight sky, and observations of Magellanic Cloud standard stars were obtained in each filter. The images were reduced using DAOPHOT (Stetson 1987), since we found a profile-fitting technique to be essential given the particularly poor seeing ($\sim 2-3$") during most of the run (see Sec. 3.2). We show in Fig. 1 an I band finding chart for the target (Star 1), and the star relative to which we performed differential photometry (Star 2) - see Sec. 3.2.

3 RESULTS

3.1 Average spectra

We show in Fig. 2 the variance-weighted average of our four 1994 blue spectra; the continuum has been normalised, but the spectra are not flux calibrated. HeI absorption is highly prominent, being observed at $\lambda\lambda$4388, 4471, 4713, 4922, 5016 and 5048. We see also weaker absorption lines of of SiIII $\lambda\lambda$4553,4568,4575 and OII λ4415-17 and λ4639-42. The absorption at $\lambda \sim$4650 is ambiguous, possibly arising from OII λ4650 or the CIII λ4647-51 absorption blend.

In emission, Hβ appears very strongly, but with broad underlying absorption. There is evidence for FeII λ5018 in emission; however, if this is present, we might also expect to see features due to this ion at $\lambda\lambda$4489-91, 4508-23, 4584 and 4629. There is no obvious emission at these wavelengths (save perhaps at λ4584), but a higher signal-to-noise ratio spectrum would be required to conclusively confirm the presence of this species.

The single blue observation obtained in Jan 1996 suffers from very poor signal-to-noise and is not shown. However, we do still see Hβ in emission, and some of the stronger HeI absorption lines, consistent with the spectra obtained ~ 1 year earlier.

In Fig. 3, the variance-weighted average of the two 1994 red spectra is presented. Hα appears very strongly in emission, consistent with CTIO Schmidt narrow-band filter imaging data obtained in 1993 Dec (Hughes, private communication). We do not see evidence for any intrinsic structure in this line. The absorption at $\sim 6270-6295$ Å is an atmospheric feature, but there are no other obvious spectral features.

3.2 Optical Photometry

Differential photometry was performed relative to Star 2 (see Fig. 1). We used observations of a standard star from the only photometric night (1996 Jan 28) to calibrate the local standard, for which we measure $V = 16.51$, $B-V = 0.82$ and $V-R = 0.49$. However, we estimate that a systematic error of $\lesssim 0.05$ mags is possible, given the paucity of photometric standard star observations.

We note that RX J0059-71 has a close companion about 4" to the south-east (Star 3 of Fig. 1). Although these two stars were not fully resolved on all our data frames, we were able to subtract the contaminant star through a profile fitting technique, in the V and R bands. The magnitudes of Star 1 thus derived were consistent with those obtained from the fully resolved frames, hence we believe the deblending procedure to be effective. We estimate that Star 3 has $V \sim 16.8$, and $V-R \sim 0.6$; however, we were unable to obtain an accurate measurement of its B magnitude, since it appeared almost totally blended with Star 1 on all frames.

We list in Tab. 2 the nightly colours of Star 1 for the period 1996 Jan 24-29 (blended with the light of Star 3 in the case of the B band). We conclude that there are no significant magnitude or colour variations, within the 1σ statistical errors, during this period. From all the optical photometry, we derive mean values of $V = 14.08 \pm 0.02$ and $V-R = 0.05 \pm 0.02$ for Star 1. The average blended magnitude in B is 14.13 ± 0.03; if Star 3 contributes a similar fraction to the blended light as in the V band, the correction to this value would be ~ 0.08 mags.

3.3 Spectral Classification and Line Measurements

The presence of neutral helium lines in the spectrum of Star 1 clearly establishes the optical counterpart as a B-type star. Furthermore, its optical brightness of $V \sim 14.1$ corresponds to an absolute visual magnitude of ~ -4.9 (for an SMC distance of 60 kpc and E_{B-V} of 0.03; see e.g. Westerlund 1991). Thus, the implied spectral type is around B0-B1 III (Jaschek & Jaschek 1987).

The presence of the Balmer lines in emission is a clear indicator that the optical counterpart is a Be star (the absolute visual magnitude rules out the possibility that it is a supergiant, since these also show Hα emission). The absorption lines of ionized Si, O and possibly C are entirely consistent with this classification, as is the probable Fe II emission, which can occur in Be stars of spectral type B0-B5 (Jaschek & Jaschek 1987). The relatively strong OII λ4639-42 absorption favours a spectral type of B1 III rather than B0 III, since this feature appears to be absent in the latter class (Yamashita, Nariai & Norimoto 1977). By this argument, we favour the identification of the $\lambda \sim 4650$ feature with OII λ4650, rather than CIII. A most likely spectral type of B1 III is thus implied.

The equivalent widths of the prominent spectral lines were measured from the average spectra of Fig. 2 and Fig. 3 by summing the flux in the line after normalising the continuum. The results are summarised in Tab. 3. We do not attempt a measurement for Hβ since the underlying absorption introduces large inaccuracies. The average value for Hα of 15.23 ± 0.20 Å is consistent with that found in 1993 Dec (Hughes 1994).

We investigated the velocities of the strongest spectral lines through cross correlation with the average spectrum. No significant changes in the velocities of any of the lines

were observed over the two nights of observations. The mean velocity of Hα is $v = 155 \pm 2\,\mathrm{km\,s^{-1}}$ and of He I 4471 is $v = 147 \pm 10\,\mathrm{km\,s^{-1}}$. These may be compared to the line-of-sight velocity of the SMC of $\sim 168\ \mathrm{km\,s^{-1}}$ (Allen 1973).

A single Gaussian fit to the Hα average profile yielded a width of $\sigma = 119 \pm 2\,\mathrm{km\,s^{-1}}$ (this includes the instrumental broadening due to the detector resolution of ~ 1.3 Å or $\sim 40\,\mathrm{km\,s^{-1}}$). Whilst it is true that many Be stars have highly rotationally broadened profiles, this is not always the case, particularly in binary systems (e.g. Jaschek & Jaschek 1987). The Hβ profile is complex, hence it is difficult to obtain reliable measurements. However, a reasonable fit was achieved using two Gaussian functions to fit the narrow emission and broad absorption components. The central velocities and standard deviations of these Gaussians are $v = 132 \pm 2\,\mathrm{km\,s^{-1}}$ and $\sigma = 237 \pm 33\,\mathrm{km\,s^{-1}}$ for the absorption component, and $v = 157 \pm 2\,\mathrm{km\,s^{-1}}$ and $\sigma = 68 \pm 3\,\mathrm{km\,s^{-1}}$ for the emission component.

4 DISCUSSION

The identification of RX J0059-71 with a Be star makes this the third Be/X-ray binary known in the Magellanic Clouds, the other two being A0538-66 (e.g. Charles et al. 1983) and RX J0502.9-6626 (Schmidtke et al. 1995). The former system is a transient, with an orbital period of 16.7 d and spectral type B2 III, showing characteristic X-ray and optical behaviour in its active and quiescent states. Our optical spectrum of RX J0059-71 more closely resembles that of A0538-66 in its off-state (see Fig. 7 of Corbet et al. 1985), in terms of the absorption lines present, lack of He II 4686 emission and absence of any P Cyg type profiles. However, in our spectrum of RX J0059-71, we see Hβ strongly in emission, whereas this line appears in absorption in the quiescent A0538-66 spectrum of Corbet et al. (1985).

More importantly, the X-ray spectrum of RX J0059-71 is totally unlike any of the other known Be/X-ray systems, the existence of a luminous supersoft component being, at present, unique to RX J0059-71. Kylafis (1996) has suggested a model for RX J0059-71, in which the supersoft emission arises from a torus of optically thick material surrounding the neutron star, with the harder pulsed emission resulting from direct observation of the stellar surface along the axis of the envelope. However, it is currently unclear why this system should exhibit such anomalous behaviour. In view of this fact, we have considered the possibility that the supersoft emission may actually arise from the close (~ 4") companion to RX J0059-71 (Star 3 in Fig. 1). We have only two very low quality blue spectra of this object, taken through poor seeing and variable cloud. No obvious spectral features could be distinguished above the noise; however, our optical photometry does suggest that this star is quite blue. Whilst the chance coincidence of two such unusual stars seems unlikely, further spectroscopic observations would be desirable to conclusively eliminate this possibility.

Corbet (1984) has derived a relation between the pulse and orbital periods of the Be/X-ray systems. If this relation applies to RX J0059-71, an orbital period of ~ 15 d is expected (see Fig. 3 of van den Heuvel & Rappaport 1987). However, it is not at all clear that this correlation applies in RX J0059-71, if indeed this system is partially surrounded by a thick disk (see also A0538-66; Corbet 1986).

5 CONCLUSIONS

We have identified a B1 III emission star as the probable optical counterpart of the supersoft SMC pulsar RX J0059-71. An orbital period of ~ 15 d is predicted from the pulse period, although it is not clear that this calculation is applicable in this highly non-typical Be/X-ray system. Further optical spectroscopic and photometric observations are essential in order to: (*i*) search for a long term modulation ($\sim$ tens of days, which is the typical orbital period range for the Be/X-ray systems), (*ii*) investigate changes in the absorption/emission lines and colours, particularly in relation to the X-ray variability, and (*iii*) eliminate the possibility that the close companion of the Be star may actually be the source of the supersoft emission.

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Table 1. Journal of Spectroscopic Observations

Date	UT Start	Exp (s)	Waveband
1994/11/30	09:53	600	6108-6863
1994/11/30	10:06	”	4364-5095
1994/11/30	10:19	”	4364-5095
1994/12/01	09:46	”	6108-6863
1994/12/01	09:59	”	4364-5095
1994/12/01	10:10	”	4364-5095
1996/01/19	11:31	”	4287-5052

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Table 2. Optical photometry of RX J0059-71 (Star 1)

Date	B (+ Star 3)	V	R
	($\pm$0.04)	($\pm$0.03)	($\pm$0.02)
1996/01/24	14.17	14.06	14.03
1996/01/25	14.16	14.11	14.03
1996/01/26	14.12	14.09	14.03
1996/01/27	14.08	14.11	14.03
1996/01/28	14.13	14.05	14.02
1996/01/29	14.12	14.06	14.04

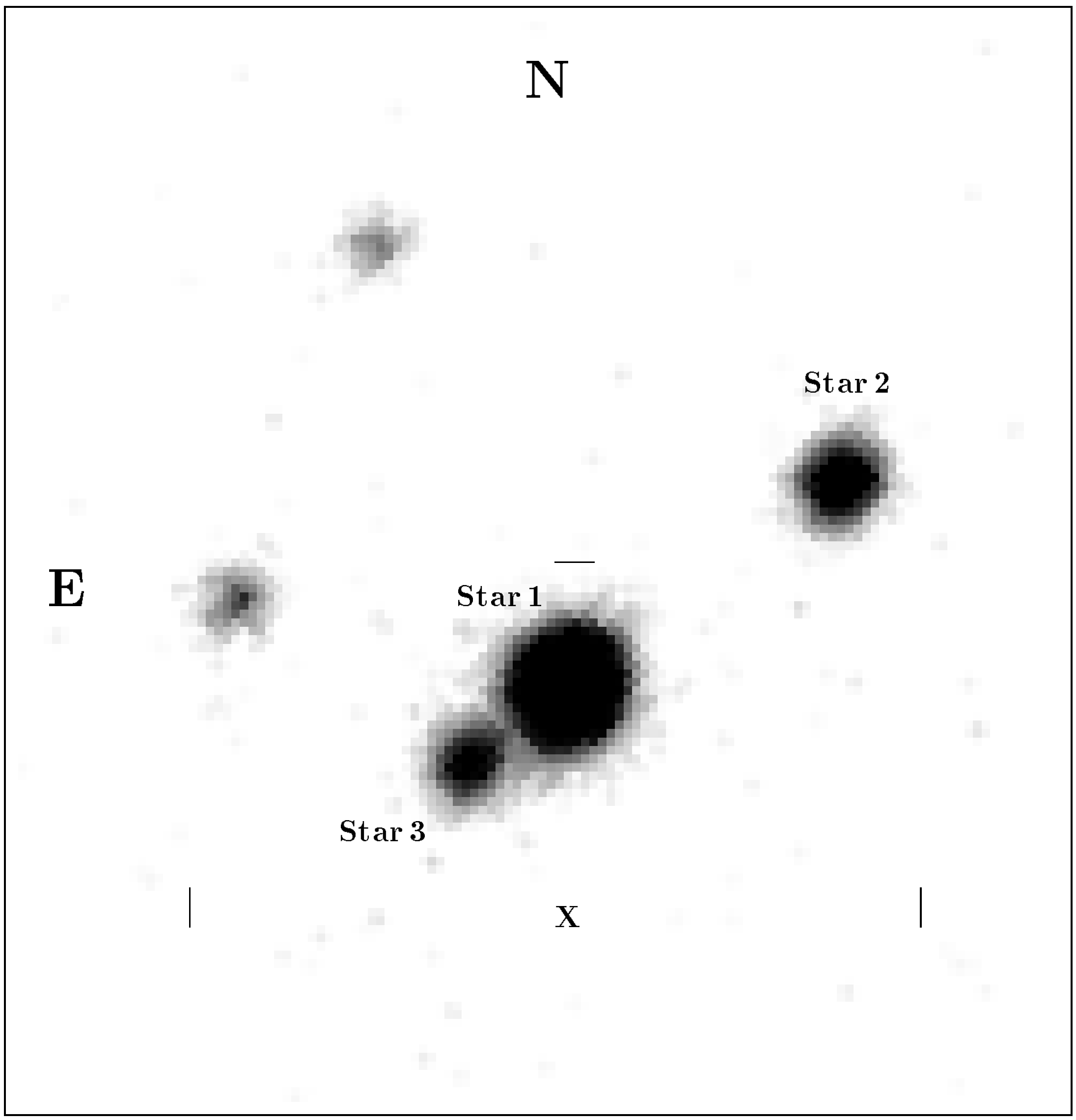
Table 3. Equivalent width measurements of 1994 spectra

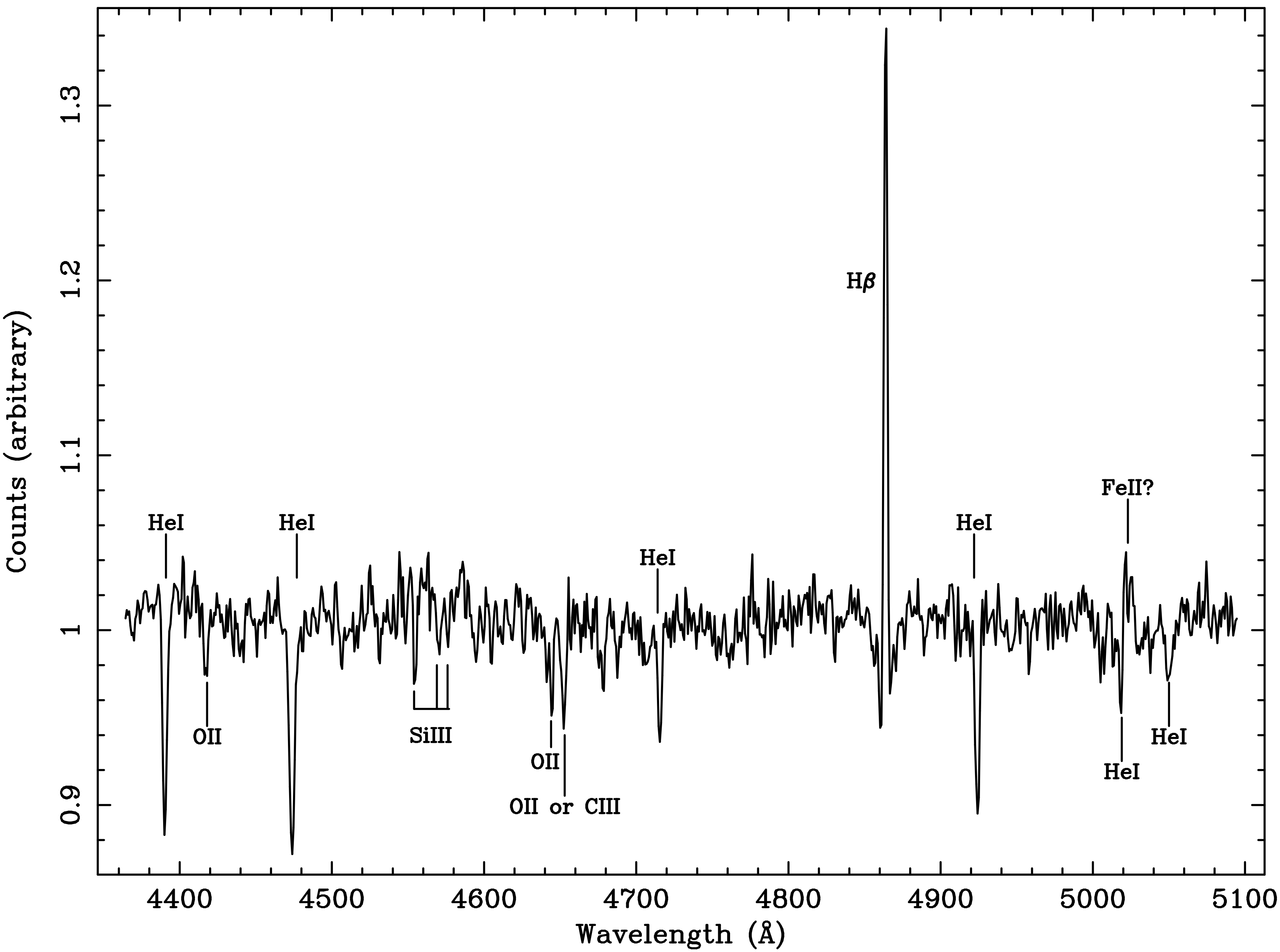
Line	Average EW (Å)
HeI 4387	$+0.34 \pm 0.04$
HeI 4471	$+0.65 \pm 0.04$
HeI 4713	$+0.23 \pm 0.03$
HeI 4921	$+0.36 \pm 0.03$
Hα	-15.23 ± 0.20

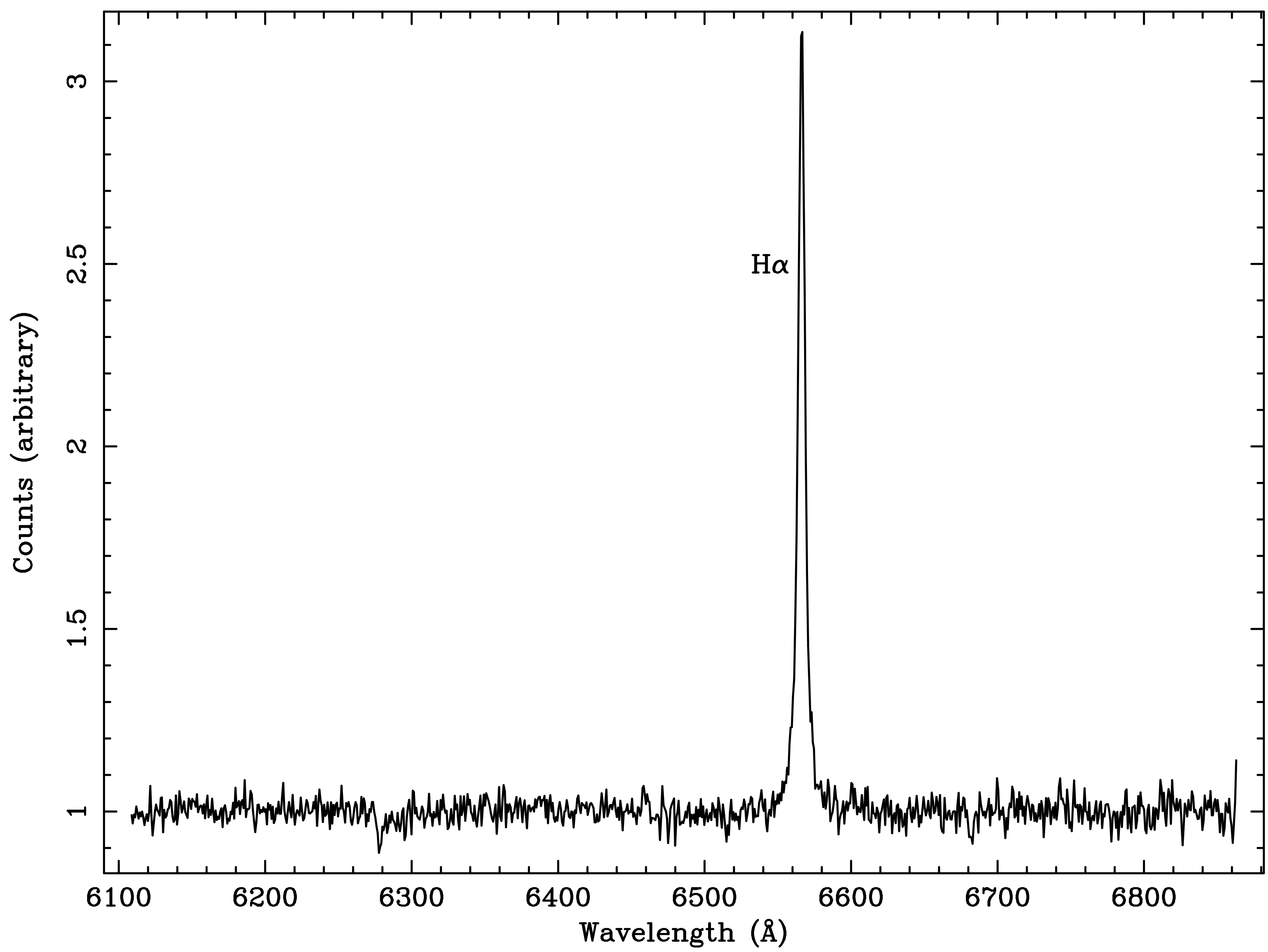
Figure 1. Finding chart for RX J0059.2-7138 (Star 1). The image was taken in the I-band with the SAAO 1.9 m + UCT CCD and covers an area of sky $\sim 0.5' \times 0.5'$. North is up, east to the left. The X-ray position (J2000: 00 59 12.9, -71 38 50) is marked with a cross, with the short horizontal and vertical lines indicating the uncertainty in the declination and right ascension respectively. Differential photometry was performed relative to Star 2. Note the close companion of RX J0059-71 about 4” to the south-east (Star 3). There are no other stars within the X-ray error circle brighter then $V \sim 18$.

Figure 2. Average blue spectrum of RX J0059-71 from observations taken in 1994. The region $4364 - 5095$ Å is covered with a resolution of ~ 1.3 Å. The spectrum is dominated by HeI absorption and weak lines of OII and SiIII. In emission, Hβ λ4861 appears very strongly, with broad underlying absorption. FeII lines may appear in emission, as evidenced by the feature at λ5018.

Figure 3. Average high resolution ($\sim$ 1.3Å) red spectrum. Hα appears very strongly in emission, but we do not see evidence for any intrinsic structure. The absorption at $\sim 6270 - 6295$ Å is an atmospheric feature.


N
E
Star 2
Star 1
Star 3
X


HeI
OII
HeI
SiIII
OII
OII or CIII
HeI
Hβ
HeI
FeII?
HeI
HeI
Counts (arbitrary)
Wavelength (Å)
0.9
1
1.1
1.2
1.3
4400
4500
4600
4700
4800
4900
5000
5100


Hα
Counts (arbitrary)
1
1.5
2
2.5
3
6100
6200
6300
6400
6500
6600
6700
6800
Wavelength (Å)